1 **Geochemical identification criteria for "peperino" stones employed in ancient Roman**
2 **buildings: a Lapis Gabinus case study**

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13 **Abstract**

14 Lapis Gabinus is a durable volcanic stone originally exploited and employed in construction at
15 the ancient Latin city of Gabii. From the second century BCE it was also exported to Rome,
16 where it appears in a series of important monuments, including the Tabularium and the
17 Forum of Augustus. It is a lithified hydromagmatic-surge deposit erupted about 285.000 years
18 ago by the Castiglione Crater, 20 km east of Rome, and is similar in appearance to other local
19 rocks that geologists and archaeologists often call "peperino". In the present study we
20 establish geochemical identification criteria to classify this rock and distinguish it from the
21 other "peperini" employed by Roman builders. To this end, we have performed trace-element
22 analyses on 17 samples of Lapis Gabinus collected from outcrops at Gabii, and on 11 samples
23 representative of the other "peperino" stones occurring in the area of Rome. The resulting
24 reference dataset has been employed to construct discrimination diagrams in which the
25 geochemical compositional fields of the different rocks are defined. We then tested this

1 identification method by plotting in these diagrams the trace-element compositions of 16
2 archaeological samples of "peperino" stones collected from the buildings of ancient Gabii and
3 Rome, spanning the sixth century BCE through the first century CE. Our results show that the
4 three most common such stones (Lapis Gabinus, Lapis Albanus, Tufo del Palatino) have
5 distinct trace-element compositions and can be readily distinguished using the proposed
6 discrimination diagrams. This relatively simple and inexpensive identification method can be
7 successfully extended to other archaeological research on volcanic materials and employed
8 for wider petrographic purposes.

9

10 **Keywords:**

11 Ancient Rome, Building Stones, Lapis Gabinus, Volcanic Rocks, Trace-element Analysis

12

1. Introduction

For much of the history of Rome, beginning as early as the eighth century BCE, builders quarried the local volcanic rocks that constitute the geologic substrate of the city (Cifani 2008). These pyroclastic and lava flow deposits erupted during the Middle-Late Pleistocene activity of the Colli Albani and Monti Sabatini volcanic districts (Marra et al., 2011, and references therein). Though their presence in monuments spanning the archaic period through the imperial age has been thoroughly documented by several authors (e.g., Lanciani, 1897; Lugli, 1957; Coarelli, 1974; Cifani, 1994; Heiken et al., 2005; Jackson and Marra, 2006), the identification of the lithological units to which the different lithified tuffs belong has been traditionally based upon visual appearance, including macroscopic and, to a lesser extent, microscopic petrographic features. This is a qualitative approach which requires deep knowledge of the local geology and specific expertise on volcanic petrography and sedimentology, providing a learned, yet subjective judgment. In other words, it does not meet the highest scientific standards, since it lacks one of the basic principles on which modern science is based: verifiability of the data through replicability of results.

Indeed, several of these volcanic rocks display very similar textures, mineralogical assemblages, xenolith occurrence, and color. Furthermore, each eruptive unit is itself characterized by high variability of petrographic features and may exhibit a wide range of colors and compositional fabrics, depending on primary geological factors such as distance from the eruptive vent, morphology, and composition of the substrate, or on secondary processes such as weathering and alteration. These factors sometimes make distinguishing between lithological units problematic. Even efforts relying on more quantitative analyses, like total alkali-silica (TAS) composition and X-ray diffraction, are often insufficient to establish definitively the provenance of a volcanic rock, due to the occurrence of strong alteration processes and to the substantial similarities in the mineralogical assemblages of

1 several different products of the volcanic districts of central Italy (Peccerillo, 2005, and
2 references therein).

3 It is perhaps because of the similarities between stones, as well as the potential variability
4 within a given deposit, that archaeologists often rely on general descriptive terms (e.g. gray
5 granular tuff, red lithoid tuff) in recording ancient Roman stone construction. Such terms can
6 give an idea of the general appearance of a given stone block, but they do not designate the
7 particular deposit or quarry location from which it was extracted. Other terms commonly
8 found in the archaeological literature, such as “cappellaccio” and “peperino” are similarly
9 vague and can each describe several different volcanic deposits which appear macroscopically
10 similar (as discussed in greater detail below). The ambiguous and confusing terminology that
11 has resulted can thus obscure the underlying geological reality. While in this paper we,
12 especially when describing previous work, of necessity occasionally use these ambiguous
13 names, we encourage the use of formal geological terms, and they are preferred here
14 whenever possible (see Table 1, which collates and correlates the various archaeological and
15 geological terms relating to Roman tuffs). The present paper aims to increase our ability to
16 analyze the economy of stone quarrying and construction by testing a quantitative method for
17 accurately determining the specific geological provenance of these volcanic products.

18 To overcome the difficulty and subjectivity in identifying pyroclastic rocks, a method has been
19 recently developed (Marra et al., 2011) based on the ratio of particular immobile elements
20 (i.e.: Zr, Y, Nb, Th, Ta, TiO₂) which, unlike major elements (e.g.: SiO₂, Na₂O, K₂O, MgO), are
21 considered insensitive to alteration processes. This method has now been successfully applied
22 in several archaeological studies (Marra and D'Ambrosio, 2013; Marra et al., 2013;
23 2014a_Arch).

24 In the present work, we use this method to establish identification criteria for the so-called
25 “peperini” (“pepper-like stones”), which allow us to attribute a dimension stone to the

1 volcanic rock of origin and to designate it with the correct formational name established in
2 the recent geologic literature (Table 1; Marra et al., 2011, and references therein). The Roman
3 "peperini" include Lapis Gabinus (Peperino di Gabii, or Pietra Gabina), Lapis Albanus
4 (Peperino di Marino, or Peperino Albano), and some varieties of Tufo del Palatino (e.g.:
5 Peperino della Via Flaminia, "Peperino Grigio"; Karner et al., 2001a). Additionally, we also
6 include another volcanic rock whose archaeological name, "Sperone", is often incorrectly used
7 as a synonym for Lapis Gabinus (e.g.: Lugli, 1957). The present study is focused in particular
8 on Lapis Gabinus, an extremely hard rock (Jackson et al., 2005) that was employed for the
9 construction of several monuments in Rome (e.g.: the Tabularium, the Forum of Caesar, the
10 Forum of Augustus, the Cloaca Maxima; Lugli, 1957) and that erupted ca. 285 ka ago (Marra et
11 al., 2003) from the hydromagmatic center of Castiglione (De Rita et al., 1988) (Figure 1).

12

13 **2. The "peperino" stones**

14 Several different lithological units appearing in outcrops in the area of Rome have been
15 described under the conventional name of "peperino" in the archaeological and geological
16 literature (Table 1; see Karner et al., 2001a for a review). This term derives from the Italian
17 word for pepper and applies to all the pyroclastic-flow deposits characterized by lithified,
18 granular texture and grey color, in which white and black lithic inclusions, as well as abundant
19 feldspar and pyroxene crystals resembling peppercorns, occur (Figure 2). It is thus a general
20 term that does not specify a particular deposit or quarry location. We describe here the
21 various stones conventionally labelled as "peperino" which are included in our analysis, while
22 also drawing attention to the terminological confusion generated by the proliferation of
23 archaeological and geological terms (see Table 1).

24 The most typical "peperini" are two hydromagmatic-surge deposits erupted by the Castiglione
25 Crater and by the Albano Crater, 285 ka and 36 ka ago, respectively: "Peperino di Gabi" and

1 "Peperino di Marino" (also "Peperino albano") (Marra et al., 2003; Freda et al., 2006). These
2 pyroclastic deposits formed extremely hard rocks, known also by the archaeological names
3 Lapis Gabinus and Lapis Albanus (Lugli, 1957) (Figure 2a, b). "Peperino" has also been used to
4 describe both Tufo del Palatino and the Grottarossa Pyroclastic Sequence (Karner et al.,
5 2001a) (Figure 2 c, d), which are reported in the literature with the generic name of "Peperino
6 Grigio" (e.g.: Ventriglia, 1971) or with the similarly generic archaeological name
7 "cappellaccio". These present an appearance similar to Lapis Albanus and Lapis Gabinus, but
8 with a less lithified character. However, an extremely hard facies of Tufo del Palatino (Figure
9 2e) crops out in Grottarossa north of Rome (Karner et al., 2001a); this was previously
10 considered to be a product of the Monti Sabatini activity and is known in the literature as
11 Peperino della Via Flaminia (Mattias and Ventriglia, 1961). In this context, it is also important
12 to note that Tufo del Palatino is a geological, and not geographical, term, and outcrops are not
13 limited to the Palatine hill.

14 Another volcanic dimension stone used during the Fascist period to restore several Roman
15 monuments (e.g. the Colosseum, the Theatre of Marcellus) is so-called "Sperone" (Fornaseri et
16 al., 1963). This is a deposit of welded volcanic scoriae forming a portion of the Tuscolanio-
17 Artemisio caldera rim, near the town of Tuscolo (Figure 1), where it was used to build the
18 local amphitheater in the second century CE (Coarelli, 1981). The name "Sperone" is
19 improperly used as a synonym for Lapis Gabinus by Lugli (1957) ("Pietra a Sperone"),
20 generating significant confusion. However, "Sperone" has well distinguished macroscopic
21 petrographic features with respect to tuffs (including those described as "peperino"), being an
22 aggregate of rounded, sub-centimeter sized, poorly vesicular scoriae, resembling a
23 scoriaceous lava rather than a pyroclastic-flow or hydromagmatic-surge deposit (Figure 2f).
24 Indeed, "Sperone" is a clast supported deposit, which lacks the fine ash matrix
25 characteristically occurring in the "peperini".

De Rita and Giampaolo (2005) attributed the large blocks of tuff employed by the Roman builders in the walls of the Colosseum to "Sperone" from Tuscolo; Jackson et al. (2006) interpreted this rock to be a less welded, zeolitized facies of the scoriae deposit, and called it Tufo di Tuscolo. However, a study in progress (D'Ambrosio and Marra) has shown that the tuff employed at the Colosseum, whose petrographic features were described by Jackson et al. (2006), is Tufo Lionato, and that several blocks of "Sperone" occur only in the portions of the monument restored in the twentieth century. Indeed, there is no evidence that "Sperone" was used as a building stone in Rome prior to these modern restorations. For these reasons, we strongly recommend that the term Sperone not be used to designate Lapis Gabinus, in order to avoid further confusion.

3. Chronological employment and identification criteria of the peperini

In Rome, systematic quarrying for dimension stone began in the archaic period with the exploitation of the tuff commonly known as "Cappellaccio" (Lanciani, 1897; Coarelli, 1974; Lugli, 1957; Cifani, 1994), a stone which Marra and Rosa (1995) identified as the pyroclastic-flow deposit of Tufo del Palatino, from an eruption within the Colli Albani Volcanic District. This is a poorly to moderately lithified volcanic rock, depending on the outcrop location, and typically displays horizontal lamination, which makes it particularly easy to cut in homogeneously thick dimension stones (Figure 2c). However, due to its relative softness and pervasive cleavage, this rock undergoes pronounced and rapid weathering. For this reason, its use ceased as improved quarrying techniques and access to deposits further from Rome allowed the exploitation of more durable rocks, and beginning in the fourth century BCE it was replaced by the lithified pyroclastic rocks of the Monti Sabatini volcanic district which crop out in northern Rome (i.e.: Tufo Giallo della Via Tiberina and Tufo Rosso a Scorie Nere, corresponding to "Tufo di Grottaoscura" and "Tufo di Fidene"), and, probably, by Lapis

1 Albanus (Lugli, 1957; see Karner et al., 2001a for a discussion of the introduction of Lapis
2 Albanus). By the second century BCE, Tufo Lionato and Lapis Gabinus dimension stones were
3 also employed (Lugli, 1957; Coarelli, 1995), although an early use of Tufo Lionato in rubbles,
4 as well as in isolated polygonal blocks, is reported for the sixth century BCE third phase of
5 the walls at the Palatine slope (Terrenato, 1995).

6 The stones typically described as “peperini” (i.e.: Lapis Albanus, Lapis Gabinus) are
7 characterized by higher uniaxial compressive strength than Tufo Lionato and the other tuffs
8 from the Monti Sabatini district that were exploited in Rome, a fact that favored their
9 employment in architectural elements sustaining high pressures, such as piers, weight-
10 bearing walls, and arches (Jackson and Marra, 2006). Remarkably, experimental data
11 reported in Jackson et al. (2005) indicated that the uniaxial compressive strength for Peperino
12 della Via Flaminia is higher than those for Lapis Albanus and Lapis Gabinus. It is therefore not
13 possible to exclude the possibility that the more lithified facies of Tufo del Palatino was
14 exploited and used in the realization of particularly resistant dimension stones, either before
15 or after the fourth century BCE.

16 The problems in identifying the different “peperini” employed as dimension stones in ancient
17 Rome have been partially discussed in a paper by Karner and colleagues (2001b), in which the
18 similarity between the more lithified facies of Tufo del Palatino (e.g. Peperino della Via
19 Flaminia) and Lapis Albanus was addressed with respect to the interpretation of the age and
20 origin of the Tullianum, the oldest portion of the Mamertine Prison (Fortini, 1988). However,
21 the possibility that the rock employed to build the Tullianum was Tufo del Palatino, rather
22 than Lapis albanus, was ruled out by means of its $^{40}\text{Ar}/^{39}\text{Ar}$ age determination (Karner et al.,
23 2001b). One sample collected from a block of the Tullianum wall yielded age of 36 ± 1 ka,
24 identical to that yielded by a sample of Lapis Albanus collected in the ancient Roman quarries

1 in Marino, ruling out the use of Tufo del Palatino, which has a radiometric age of 530 ± 2 ka
2 (Karner et al., 2001a; Marra et al., 2009).

3 The same paper by Karner and colleagues (2001) provides another example of the difficulty in
4 recognizing different pyroclastic rocks characterized by similar macroscopic petrographic
5 appearance. The authors demonstrate that the "cappellaccio" tuff occurring on the Palatine
6 Hill, in which the so-called "huts" that are considered the remains of the earliest settlement in
7 Rome were excavated (Carandini, 2011; Alessandri, 2013), is not Tufo del Palatino, but a
8 different pyroclastic-flow unit erupted by the Monti Sabatini Volcanic District: the Grottarossa
9 Pyroclastic Sequence. This volcanic deposit displays petrographic features (i.e.: dark grey
10 color, granular texture, occurrence of white feldspar and black pyroxene crystals, diffuse
11 horizontal cleavage; see also Figure 2c, d) identical to those of Tufo del Palatino, but formed as
12 a result of an earlier eruption 518 ± 5 ka years ago (Karner et al., 2001b).

13 In the present paper we provide evidence that such laminated facies may occur also in the
14 hydromagmatic deposits of Castiglione from which Lapis Gabinus was quarried, highlighting
15 the importance of establishing objective criteria to identify these different rocks when they
16 display convergent macroscopic features.

17 While radiometric dating of the rock may be a straightforward method of identification, it is
18 an expensive procedure requiring a specialized laboratory. Moreover, hydromagmatic rocks
19 (like most "peperini") often do not contain phenocrystals in the juvenile magmatic fraction,
20 affecting the ability of samples to yield homogeneous, reliable ages (e.g.: Marra et al., 2003).

21 For example, one attempt to date a sample of Lapis Gabinus produced unreliable results,
22 when a contaminant population of 19 xenocrysts yielded a youngest age of 373 ± 8 ka, which is
23 stratigraphically inconsistent with that of ca. 285 ka inferred from the occurrence of a tephra
24 layer within the sedimentary fill of the Castiglione crater lake (Karner, 1997; Marra et al.,
25 2003).

1 In contrast, the geochemical composition of a bulk sample of volcanic rock, on which trace-
2 element classification methods are based, can be rapidly obtained at inexpensive cost in
3 several commercial laboratories, and the identification of the provenance of the rock can be
4 achieved through the use of simple discrimination diagrams from the literature (e.g.: Zr/Y vs,
5 Nb/Y; Zr/TiO₂ vs Nb/TiO₂, Th/Ta vs Nb/Zr; Marra et al., 2011; 2013; 2014; Marra and
6 D'Ambrosio, 2013).

7 In the present work, we use this method to provide classification for the different "peperini"
8 (Peperino di Gabi, Peperino di Marino or Peperino Albano, Peperino della Via Flaminia or
9 Peperino Grigio), with a particular focus on Lapis Gabinus. With this goal in mind, we
10 performed an extensive sampling of this rock at the archaeological site of Gabii (Mogetta and
11 Becker, 2014) located near the Castiglione crater, collecting fifteen samples from the ancient
12 quarries along the crater rim, two samples from the bedrock at the excavation site, and three
13 samples from the walls of the local archaeological structures. To extend the archaeological
14 dataset of analyses on this rock, we collected three samples of dimension stones identified as
15 Lapis Gabinus from the Fora of Caesar and Augustus (Lugli, 1957). Moreover, we collected
16 four samples corresponding to as many different building stones that were reported as
17 "peperini" in the Sant'Omobono archaeological site (Terrenato et al., 2012), and one sample of
18 a "peperino-like" rock employed in the concrete foundation of the Tabularium, all to be
19 compared to the samples from outcrops at Gabii.

20 Finally, in order to provide a mean of classification for all the different "peperino" rocks by
21 defining their compositional fields in the different discrimination diagrams, we have
22 complemented the dataset derived from the literature with 11 new trace-element analyses on
23 samples of Lapis Albanus, Tufo del Palatino, Sperone, and Tufo Lionato. We also have
24 analyzed two samples of "cappellaccio" stones collected from the original basement of the
25 Temple of Jupiter Capitolinus (sixth century BCE), and from a remnant of the "Servian" walls

(sixth century BCE) preserved in the underground level of Stazione Termini, as well as one sample of Lapis Albanus which is part of the same rock sample collected at the Tullianum and dated 36 ka by Karner et al. (2001). A complete list of the 16 archaeological and 27 outcrop samples analyzed in this work is provided in Tables 2 and 3, respectively.

4. Sampling for the geochemical study

4.1 The archaeological site of Gabii

The city-state of Gabii was both a neighbor of, and a rival to, Rome in the early part of the first millennium BCE. Located right on the rim of the Middle-Pleistocene hydromagmatic volcanic crater of Castiglione (Figure 1), the site of Gabii was occupied since at least the tenth century BCE until its decline in the second and third centuries CE. Since Gabii eventually came under the power of Rome – first as a member of the Latin League and later as a town with municipal status – numerous important intersections exist between the two cities. The Gabii Project is an ongoing, international archaeological initiative (Becker et al., 2009; Mogetta and Becker, 2014) aimed not only at exploring and understanding the archaeology of the city of Gabii but also situating and contextualizing its role in the wider orbits of central Italy and the Roman Empire. In this context, the exploitation and employment of the local building stone (Lapis Gabinus) in several important monuments in Rome beginning in the second century BCE represents a significant development.

In the present paper, we attempt to establish objective geochemical criteria for identifying this rock with respect to other, similar stones employed in ancient Roman times. We therefore collected samples of Lapis Gabinus from several ancient quarries located along the eastern side of the crater (Figure 3a), exposing the hydromagmatic-surge deposit erupted by the Castiglione center.

1 Six rock samples were collected in as many quarries (Figure 3a), while eight additional
2 samples were collected from a single, previously buried quarry face discovered within the
3 archaeological excavations conducted by the Gabii Project. Since this quarry was afterwards
4 backfilled for safety reasons (and thus inaccessible for future study), it was investigated in
5 greater detail, with samples taken at ca. 50 cm vertical intervals (Figure 3b).
6 Additional samples were taken from the excavated structures at Gabii (Figure 3c).
7 Remarkably, while many of the dimension stones from the ancient buildings display the
8 typical appearance of Lapis Gabinus, a few present a crumbly, laminated texture, with the
9 absence of lava lithic clasts and other inclusions and the presence of feldspar crystals, giving
10 these stones an appearance similar to "cappellaccio", virtually identical to that of Tufo del
11 Palatino (Figure 3d-d').
12 However, this same texture characterized the finer, upper portion of the geologic substrate of
13 Lapis Gabinus exposed at the excavation site (Figure 3e), suggesting that the stones were cut
14 from this upper facies of the hydromagmatic deposit. In order to assess this, two samples
15 were collected from these dimension stones (G1, G2), along with two samples from the
16 outcropping deposit showing the same laminated aspect (G4, G5), and these samples were
17 analyzed for major and trace elements. A third, typical Lapis Gabinus dimension stone was
18 also sampled (G3) and analyzed for comparison.

20 **4.2 The archaeological site of Sant'Omobono**

21 The Area Sacra of Sant'Omobono, located on the bank of the Tiber River just east of the Tiber
22 Island, in the Forum Boarium (Figure 1), is being investigated by an international research
23 team (Terrenato et al., 2012). The new season of work aims at a full reconsideration of the
24 archival, monumental and artifactual evidence from this important archaeological site, which
25 preserves some of the earliest evidence of human activity in Rome. At this site, in close

1 proximity of the river harbor, very early occupation was followed in the mid-sixth century
2 BCE by the construction of one of the earliest stone-built temples in Rome. This 'archaic
3 temple' was replaced by twin temples dedicated to the goddesses Fortuna and Mater Matuta
4 between the end of the sixth and the beginning of the fifth century BCE, when the area was
5 raised by several meters and completely reorganized. After the construction of the twin
6 temples, the sanctuary was modified and redecorated several times down to the second
7 century CE, though its basic layout seems to have remained relatively unchanged.

8 A very wide selection of the different volcanic stones employed in Rome is currently visible at
9 S. Omobono in the remains of the successive architectural phases, including the three main
10 kinds of peperino that have been sampled in this study, along with a block of Tufo Lionato
11 that previous archaeological reports had indicated as peperino.

12 One sample of a typically crumbly "cappellaccio" block (SO-1) was collected from a massive
13 tuff platform built before the podium of the twin temples, probably at the end of the sixth
14 century BCE (Terrenato et al., 2012) (Figure 4b). Two samples of much harder, peperino-like
15 material were collected from as many blocks belonging to the twin temples: SO-2 is a part of
16 the outer wall of the podium of the twin temples dating to the early fifth century BCE (Figure
17 4c), while SO-3 comes from a small staircase abutting the main podium and probably added at
18 a late date that cannot be determined precisely (Figure 4d). A fourth sample (SO-4, Figure 4e)
19 was collected from a block on which the first century CE travertine floor of the sanctuary is
20 based. A careful examination of this last sample, the un-altered core of which displays the
21 typical orange color (Freda et al., 1997; Marra et al., 2011), suggested its attribution to Tufo
22 Lionato (=Tufo dell'Aniene, Lugli, 1957), despite previous identification as peperino. A certain
23 resemblance with Lapis Gabinus (hence the mistaken attribution, probably) is given by the
24 high degree of lithification, the dark grey color of the external surface, and by the occurrence
25 of abundant lithic inclusions similar to those occurring in hydromagmatic rocks.

1 **4.3 Tabularium**

2 The so-called Tabularium sits at the western edge of the Roman forum, at the base of the
3 Capitoline hill. From the forum, a massive ashlar wall can be seen at the basement level
4 supporting a pillared arcade, atop which one or more temples once stood in the area now
5 occupied by the Senatorial Palace (Tucci, 2005; Coarelli 2010). The structure was built in the
6 early first century BCE, and an inscription connects it to the state archive (*tabularium*) of
7 Rome, though the archive itself may have been housed in a separate structure nearby which is
8 no longer extant (Coarelli, 2010).

9 Lapis Gabinus has long been identified, along with Tufo Lionato, in the large basement
10 structure and in the pillared arcades (Lugli, 1957). A peperino-like stone is also extensively
11 employed as the coarse aggregate in the concrete of the foundation, but due to the small
12 dimension of these rubble stones, it is difficult to establish whether it is Lapis gabinus or
13 another, similar rock. One sample of this coarse aggregate (TA) was separated from the lime
14 matrix and analyzed for trace elements.

16 **4.4 Fora of Caesar and Augustus**

17 Roman builders also employed a significant amount of Lapis Gabinus in both the Forum of
18 Caesar and the Forum of Augustus (Lugli, 1957; Jackson and Marra 2006). In the mid-first
19 century BCE Julius Caesar oversaw the construction of a new public space just north of the
20 Roman forum, consisting of a rectangular colonnaded square with a row of shops (*tabernae*)
21 along one side. A temple to Venus Genetrix, ancestral goddess of the *gens Julia*, dominated the
22 northwestern side of the forum. Lapis Gabinus is present in the piers and flat arches of the
23 *tabernae* (alongside travertine and Tufo lionato) and in at least one corner of the temple
24 podium.

The Forum of Augustus was dedicated in 2 BCE after several decades of construction. Only the northeastern section of the forum is preserved today, including the Temple of Mars Ultor at the back of the square, a massive boundary wall behind it, and porticoes on either side with semicircular exedras. The square was meant to provide additional public space while also glorifying the emperor's achievements. Lapis Gabinus can be found in the boundary wall behind the temple, extending into the eastern exedra, as well as in the corners of the podium (which otherwise is built of Tufo Lionato).

For the present study, we collected and analyzed one sample of the stone from the Forum of Caesar (FC1, from one of the piers of the *tabernae*) and two samples from the Forum of August (FA1, from the eastern exedra, and FA2, from the western corner of the temple podium).

5. Methods

Bulk samples of the volcanic rocks were analyzed for major and trace element composition at Activation Laboratories, Canada by Lithium Metaborate/Tetraborate Fusion ICP-MS. The fused samples were diluted and analyzed by Perkin Elmer Sciex ELAN 6000, 6100 or 9000 ICP/MS. Three blanks and five controls (three before the sample group and two after) were analyzed for each group of samples. Wet chemical techniques were used to measure the loss on ignition (LOI) at 900°C. International rock standards have been used for calibration and the precision is better than 5% for Rb and Sr, 10% for Ni, Zr, Nb, Ba, Ce, and La, and 15% for the other elements. Full geochemical data delivered in three successive sets of analyses are provided as supplementary online material (Appendix 1A-B-C).

6. Results and discussion

6.1 Classification diagrams

1 A Zr/TiO₂ vs Nb/TiO₂ classification diagram (Marra et al., 2015) has been produced by
2 plotting data achieved through trace-element analyses performed on a representative set of
3 28 samples collected in the field, aimed at establishing comparative compositional fields for
4 the archaeological samples of volcanic rocks employed as dimension stones investigated in
5 this paper (Figure 5). These include:
6 17 samples of Lapis Gabinus collected from Gabii at the Castiglione Crater;
7 4 samples of Tufo del Palatino, including 2 samples (CH1, CH2) collected at the outcrop of Via
8 della Consolazione on the southeastern slope of the Capitoline Hill, and 2 samples (DK, PVF) of
9 the Peperino della Via Flaminia facies collected in the Tiber River valley north of Rome;
10 3 samples of Lapis Albanus collected at the ancient Roman quarries of Marino;
11 1 sample of Sperone collected at the Roman quarries in the village of Tuscolo;
12 3 samples of Tufo Lionato collected at the southeastern slope of the Capitoline Hill (VDC), and
13 at the ancient Roman quarries located on the Aniene River valley at Salone and Tor Cervara
14 (LSA, LTC).
15 The dataset has been integrated with three existing analyses from literature on Tufo del
16 Palatino and on Tufo Lionato. Table 2 presents sample provenance, either from the literature
17 or collected for the present work.
18 Figure 5 shows a very satisfactory result. The three compositional fields of the "peperini"
19 (Lapis Gabinus, Lapis Albanus and Tufo del Palatino) are clearly distinguished from one
20 another, and with the composition of the Sperone sample plotting far from them. In contrast, a
21 certain degree of overlapping exists between Tufo del Palatino and Tufo Lionato, particularly
22 when previous analyses on these rocks (light gray symbols) are considered. Indeed, when
23 limited to the homogeneous set of samples analyzed in the present study (dark gray symbols),
24 the compositional field for Tufo del Palatino (bounded by the dashed line) is clearly distinct
25 from that for Tufo Lionato. More generally, the three samples from literature seem to display

a systematic offset, plotting far to the right in the diagram of Figure 5, which may be due to different analytical procedures (i.e.: samples *101* and *tt* analyzed with XRF technique in Freda et al., 1997), or to analytical uncertainty (sample VP analyzed with the same procedure in Marra et al., 2011). When these samples are neglected, very tight Zr/TiO₂ vs Nb/TiO₂ compositional fields characterize the four investigated lithological units, with a particularly well-defined field for Lapis gabinus, whose samples plot very close to each other.

6.2 Lithological identification of the archaeological samples

In order to provide a classification scheme for the investigated archaeological samples, their trace-element compositions have been plotted in the Zr/TiO₂ vs Nb/TiO₂ discrimination diagram of Figure 6a, as well as in two other diagrams providing further information. These are the Th/Ta vs Nb/Zr and the Zr/Y vs Nb/Y classification diagrams (Marra et al., 2011) (Figure 6b and c, respectively), in which the compositional fields of the volcanic products are displayed following the same procedure adopted to build the diagram in Figure 5. Finally, all the samples analyzed in the present study, either from outcrops or from monuments, are plotted in the total alkali vs silica (TAS) diagram of Figure 7. Unlike the previous classification diagrams, this diagram is based on major element compositions which are affected by a high degree of variability, as a consequence of the more or less intensive alteration processes experienced by the samples; nevertheless, it provides some useful information, as discussed below.

Figure 6a shows that all the samples collected from the archaeological structures excavated in Gabii, including the typical "peperino" facies as well as the "cappellaccio-like" laminated facies, along with the three samples collected at the Forums of Caesar and Augustus, plot within or very close to the Lapis Gabinus compositional field defined by the outcrop samples (dashed contour line). Any possible uncertainty due to the proximity of the adjacent

1 compositional field of Lapis Albanus is dispelled by the combined use of the Th/Ta vs Nb/Zr
2 diagram of Figure 6b. Here, all the above-mentioned samples display Th/Ta>45, well above
3 the threshold value (dashed sub-horizontal line in Figure 6b) for the compositional field
4 established by Marra and D'Ambrosio (2013) for the products of the entire eruptive sequence
5 of the Alban crater, as also confirmed by the Lapis Albanus samples analyzed in this work.
6 The solid contour line in Figure 6a can thus be considered an implemented compositional
7 field for Lapis Gabinus, to be used for future studies. A distinct, restricted compositional field
8 for Lapis Albanus is established in Figure 6a and b based on the four samples analyzed in this
9 work, including the archaeological sample TA collected at the Tullianum, whose attribution to
10 this lithological unit is granted by its radiometric age as determined in Karner et al. (2001b).
11 Similarly, samples of typical "cappellaccio" stones, like those collected at the Temple of Jupiter
12 Capitolinus and at the Servian Walls (TJ, TS), unambiguously display compositions very close
13 to, or within, the Zr/TiO₂ vs Nb/TiO₂ and the Th/Ta vs Nb/Zr compositional fields of Tufo del
14 Palatino (Figure 6a and 6b, respectively), allowing for reliable identification.
15 Remarkably, the diagrams of Figure 6 provide clear evidence that the uncertain sample
16 collected from the foundation of the Tabularium (TA) should be attributed to Tufo del
17 Palatino, and that the sample collected from the stairs at Sant'Omobono (SO-3) is Lapis
18 Gabinus.
19 In contrast, samples of Tufo Lionato collected at Sant'Omobono (SO-4, SO-4b, SO-5)
20 significantly enlarge the compositional field based on the analyzed outcrop samples (Figure
21 6a, b). Indeed, if we were to base our attribution solely on the trace element composition in
22 these diagrams, we might ascribe them to Tufo del Palatino. However, the third
23 discrimination diagram (Figure 6c) helps to identify these samples correctly. In particular,
24 when the two samples from the literature (analyzed with a different technique) are
25 disregarded, the Tufo Lionato samples from Sant'Omobono and those from the outcrops

1 delineate a smaller Zr/Y vs Nb/Y compositional field which overlaps with that of Tufo del
2 Palatino only to a very limited extent. On the other hand, the Zr/Y vs Nb/Y diagram of Figure
3 6c provides larger areas of overlap between Lapis Albanus and Lapis Gabinus compositions,
4 resulting in a less useful method of identification for these lithologies.

5 All these considerations show that the combined use of the three discrimination diagrams of
6 Figure 6, as already noted by Marra et al. (2015) for the pozzolanaceous pyroclastic-flow
7 deposits of Rome, can provide unambiguous identification for all the various volcanic rocks
8 employed in ancient Rome, whether as dimension stone or as aggregate in concrete and
9 mortar.

10 One final point is worth making regarding the TAS compositions of the analyzed samples
11 shown in the diagram of Figure 7. While the dispersed compositional fields for four of the
12 investigated lithologies make this diagram virtually useless for the classification of altered
13 samples, we note a narrow concentration for the 8 samples (Q1-8, shaded area in Figure 7)
14 collected at the excavated quarry face at Gabii.

15 This feature suggests that alkali concentration ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) may be strongly influenced by
16 post-depositional weathering processes, reflecting the particular environmental condition
17 and providing a local "signature", which may be able to serve as a means of discrimination,
18 within the same lithology, of the specific provenance site for a given rock sample. Future
19 investigations and further analyses may verify this intriguing hypothesis. However, in light of
20 this, it is particularly interesting that the archaeological samples of Tufo del Palatino, along
21 with those collected at the Temple of Jupiter and in Sant'Omobono (TJ, SO1), and at Stazione
22 Termini (TS), show very similar TAS compositions and plot close to the outcrop samples of
23 the Capitoline Hill (CH1, CH 2). In contrast, the "anomalous" sample collected from the
24 foundation of the Tabularium (TA), characterized by a peperino-like facies, plots far from the

previous samples and displays phono-tephritic to tephritic composition similar to those for the Peperino della Via Flaminia samples (DK, PVF).

7. Conclusions

The results collected here have a number of significant implications for the archaeological study of ancient Rome. First, by establishing an inexpensive and reliable method of distinguishing between the various “peperino” tuffs of central Italy, this study opens the door to specific research questions regarding the economy of ancient stone quarrying and construction. Accurate data on the distribution of particular tuffs in Roman buildings is necessary for quantitative studies of stone block production, transportation routes, or quarry and construction techniques, for instance. The discrimination diagrams described above can serve as the basis for such distributions.

In particular, we have expanded the dataset regarding Lapis Gabinus, a crucial building stone in the Roman period, allowing for secure attribution in the face of similar stones such as Lapis Albanus. In addition, the fact that some portions of the Lapis Gabinus deposit (as well as blocks quarried therefrom) present a friable, “cappellaccio-like” appearance has not been previously observed, and demonstrates the risks inherent in visual identification. While archaeologists working in and around Rome should continue to provide detailed descriptions of building material from excavations, common descriptors such as “peperino” or “gray tufo” are insufficient, and samples of tuff building materials should be obtained where possible for potential future analysis.

At S. Omobono too, the repercussions of these studies are of the greatest importance. To offer just one example, the identification of the perimeter wall of the podium of the twin temples as Lapis Albanus is very significant as the first introduction of this material to the architecture of Rome. In short, it is reasonable expect that these new methods, when systematically applied

to the complex variety of tuffs employed in 1st millennium BCE construction in central Italy,
will open up very fruitful new opportunities for sound scholarly advancement.

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FIGURES CAPTION:

1) Map of the investigated area, showing location of the investigated monumental and archaeological areas, the principal quarry sites and the volcanic centers.

2) Photographs of different “peperino” stones:

a) Lapis Gabinus, characterized by cm-thick layers (a') in which lithic clasts concentrate; b) Lapis albanus; c) Tufo del Palatino: facies characterized by typical horizontal lamination (c'); d) Tufo del Palatino: Peperino della Via Flaminia facies; e) Grottarossa Pyroclastic Sequence; f) Sperone -not a peperino (welded scoriae deposit of the Tuscolano-Artemisio post-caldera activity). As explained in the text, the similar appearance of the stones shown in these pictures makes their visual discrimination very difficult.

3) a) Satellite view of the Castiglione Crater area showing location of the sampled quarries of Lapis gabinus (white dots) and of the excavation site; b) Map of the excavation site showing location of Quarry #7 (b'); c) "Cappellaccio-like" dimension stone.

4) Map of archaeological site of Sant'Omobono (a) and photos of sampled building stones: b) typical "cappellaccio" stone; c, d) typical "peperino" stones; e) "peperino-like" stones that the present study identifies as Tufo Lionato.

5) Zr/TiO₂ vs Nb/TiO₂, Zr/Y reference diagram (Marra et al., 2015). See Table 2 for sample provenance. Light grey symbols represent sample compositions from literature: 1) Marra et al., 2011; 2) Freda et al., 1997.

1 6) Zr/TiO₂ vs Nb/TiO₂, Th/Ta vs Nb/Zr and Zr/Y vs Nb/Y diagrams. See Table 3 for
2 archaeological sample provenance.

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4 7) Na₂O+K₂O vs SiO₂ (TAS) diagram for outcrop and archaeological samples (see Table 2 and
5 3). The narrow concentration for the 8 samples (Q1-8, shaded area) collected from the same
6 quarry face at Gabii suggests that alkali concentration may be influenced by post-depositional
7 weathering processes, providing a discriminating "local signature".

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9 TABLE 1: list of "peperino" rocks.

10 TABLE 2: List of analyzed outcrop samples

11 TABLE 3: List of analyzed archaeological samples.

12 APPENDIX 1A-B-C - Geochemical data

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

PEPERINI			
CORRECT GEOLOGICAL NAME	PROPOSED ARCHAEOLOGICAL NAME	OTHER ARCHAEOLOGICAL NAME	OTHER GEOLOGICAL NAMES
Peperino di Marino, Peperino Albano, Albano Unit 6 ^(1, 2)	Lapis albanus ⁽⁶⁾	<i>Peperino</i> ⁽⁶⁾	<i>Villa Doria Unit</i> ⁽⁹⁾
Peperino di Gabi, Hydromagmatic-surge deposit of Castiglione ⁽³⁾	Lapis gabinus ⁽⁶⁾ (italian: Pietra Gabina)	<i>Pietra Sperone, Asperone</i> ⁽⁶⁾	
Tufo del Palatino ⁽⁴⁾	Tufo del Palatino	Cappellaccio ⁽⁶⁾	<i>Tufo Granulare (Grigio), Peperino Grigio</i> ⁽¹⁰⁾ ; <i>Peperino della Via Flaminia</i> ⁽¹¹⁾
Grottarossa Pyroclastic Sequence ⁽⁵⁾	Grottarossa Pyroclastic Sequence	Cappellaccio	<i>Tufo Granulare (Grigio)</i>
Welded scoria-fall deposit of the Ticolano-Artemisio			
Sperone	Sperone	<i>Sperone Tuff</i> ⁽⁷⁾ <i>Tufo di Tuscolo</i> ⁽⁸⁾	<i>Lava Spero</i> ⁽¹²⁾

TABLE 1 - Nomenclature of the most common peperino rocks of the Roman region. In italics, the archaeological and local geological names which use should be avoided in order to eliminate confusion due to redundant and/or misleading appellation. The term "Cappellaccio" should be considered as a supplementary attribution to indicate the typical, laminated facies of Tufo del Palatino and Grottarossa Pyroclastic Sequence, as opposed to the Peperino della Via Flaminia, strongly lithified facies.

(1) Freda et al., 2006; (2) Giaccio et al., 2007; (3) Marra et al., 2003; (4) Marra and Rosa, 1995; (5) Karner et al., 2001a; (6) Lugli, 1957; (7) De Rita and Giampaolo, 2006; (8) Jackson et al., 2005; (9) De Benedetti et al., 2008; (10) Ventriglia, 1971; (11) Mattias and Ventriglia, 1970; (12) Fornaseri et al., 1963.

Table 2

SAMPLE	ROCK	LOCALITY	NOTES
G4	LG	Gabii	laminated facies
G5	LG	Gabii	laminated facies
G6	LG	Gabii	Quarry 1
G7	LG	Gabii	Quarry 2
G8	LG	Gabii	Quarry 3
G9	LG	Gabii	Quarry 4
G10	LG	Gabii	Quarry 5
G11	LG	Gabii	Quarry 6
G12	LG	Gabii	Quarry debris
Q1	LG	Gabii	Quarry 7
Q2	LG	Gabii	Quarry 7
Q3	LG	Gabii	Quarry 7
Q4	LG	Gabii	Quarry 7
Q5	LG	Gabii	Quarry 7
Q6	LG	Gabii	Quarry 7
Q7	LG	Gabii	Quarry 7
Q8	LG	Gabii	Quarry 7
CH-1	TP	Capitoline Hill	Via d. Consolazione
CH-2	TP	Capitoline Hill	Via d. Consolazione
PVF	TP	Via Filacciano	Peperino d. Via Flaminia
DK(*)	TP	Via Flaminia	Peperino d. Via Flaminia
<i>VP⁽¹⁾</i>	<i>TP</i>	<i>Viale delle Provincie</i>	<i>Roman quarries</i>
PA-A	LA	Marino	Roman quarries
PA-B	LA	Marino	Roman quarries
PA-C	LA	Marino	Roman quarries
SP-TU	SP	Tuscolo	Roman quarries
VDC	TL	Capitoline Hill	Via d. Consolazione
LTC	TL	Tor Cervara	Roman quarries
LSA	TL	Salone	Roman quarries
<i>101⁽²⁾</i>	<i>TL</i>	<i>Fioranello</i>	
<i>tt⁽²⁾</i>	<i>TL</i>	<i>Fioranello</i>	

TABLE 2 - Outcrop rock samples analyzed for major and trace-element composition in this work, and, in italics, from literature (⁽¹⁾Marra et al., 2011; ⁽²⁾Freda et al., 1997).

(*)sample dated 530±2 ka in Karner et al., 2001a.

Abbreviations: LG: Lapis gabinus; TP: Tufo del Palatino; TL: Tufo Lionato; LA: Lapis albanus; SP: Sperone.

SAMPLE	MONUMENT	ROCK	NOTES
G1	Excavated structures at Gabii	LG	laminated facies
G2	Excavated structures at Gabii	LG	laminated facies
G3	Excavated structures at Gabii	LG	
FC1	Forum of Caesar	LG	
FA1	Forum of Augustus	LG	
FA2	Forum of Augustus	LG	
SO-1	Sant'Omobono	TP	
SO-2	Sant'Omobono	LA	
SO-3	Sant'Omobono	LG	
SO-4	Sant'Omobono	TL	
SO-4b	Sant'Omobono	TL	
SO-5	Sant'Omobono	TL	
TA	Tabularium	TP	caementum in concrete foundation
TJ	Temple of Capitoline Jupiter	TP	
TS	"Servian" walls below Termini Station	TP	
TU (MAM 01)	Tullianum	LA	sample dated 36 ± 1 ka in Karner et al., 2001b

TABLE 3 - Archaeological samples analyzed for major and trace-element composition in this work.

Abbreviations: LG: Lapis gabinus; TP: Tufo del Palatino; TL: Tufo Lionato; LA: Lapis albanus.